CORRELATED ERRORS IN EARTH POINTING MISSIONS*

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ABSTRACT

Two different Earth-pointing missions dealing with attitude control and dynamics changes illustrate concerns with correlated error sources and coupled effects that can occur. On the OrbView-2 (OV-2) spacecraft, the assumption of a nearly-inertially-fixed momentum axis was called into question when a residual dipole bias apparently changed magnitude. The possibility that alignment adjustments and/or sensor calibration errors may compensate for actual motions of the spacecraft is discussed, and uncertainties in the dynamics are considered. Particular consideration is given to basic orbit frequency and twice orbit frequency effects and their high correlation over the short science observation data span. On the Tropical Rainfall Measuring Mission (TRMM) spacecraft, the switch to a contingency Kalman filter control mode created changes in the pointing error patterns. Results from independent checks on the TRMM attitude using science instrument data are reported, and bias shifts and error correlations are discussed. Various orbit frequency effects are common with the flight geometry for Earth pointing instruments. In both dual-spin momentum stabilized spacecraft (like OV-2) and three axis stabilized spacecraft with gyros (like TRMM under Kalman filter control), changes in the initial attitude state propagate into orbit frequency variations in attitude and some sensor measurements. At the same time, orbit frequency measurement effects can arise from dynamics assumptions, environment variations, attitude sensor calibrations, or ephemeris errors. Also, constant environment torques for dual spin spacecraft have similar effects to gyro biases on three axis stabilized spacecraft, effectively shifting the one-revolution-per-orbit (1-RPO) body rotation axis. Highly correlated effects can create a risk for estimation errors particularly when a mission switches an operating mode or changes its normal flight environment. Some error effects will not be obvious from attitude sensor measurement residuals, so some independent checks using imaging sensors are essential and derived science instrument attitude measurements can prove quite valuable in assessing the attitude accuracy.

BACKGROUND

Figure 1 shows the spacecraft and coordinates, and Table 1 summarizes key features of the OV-2 and TRMM spacecraft. They were both launched in 1997 and are Earth pointing missions with their primary pointing designed for collection of Earth image data in various frequency bands.

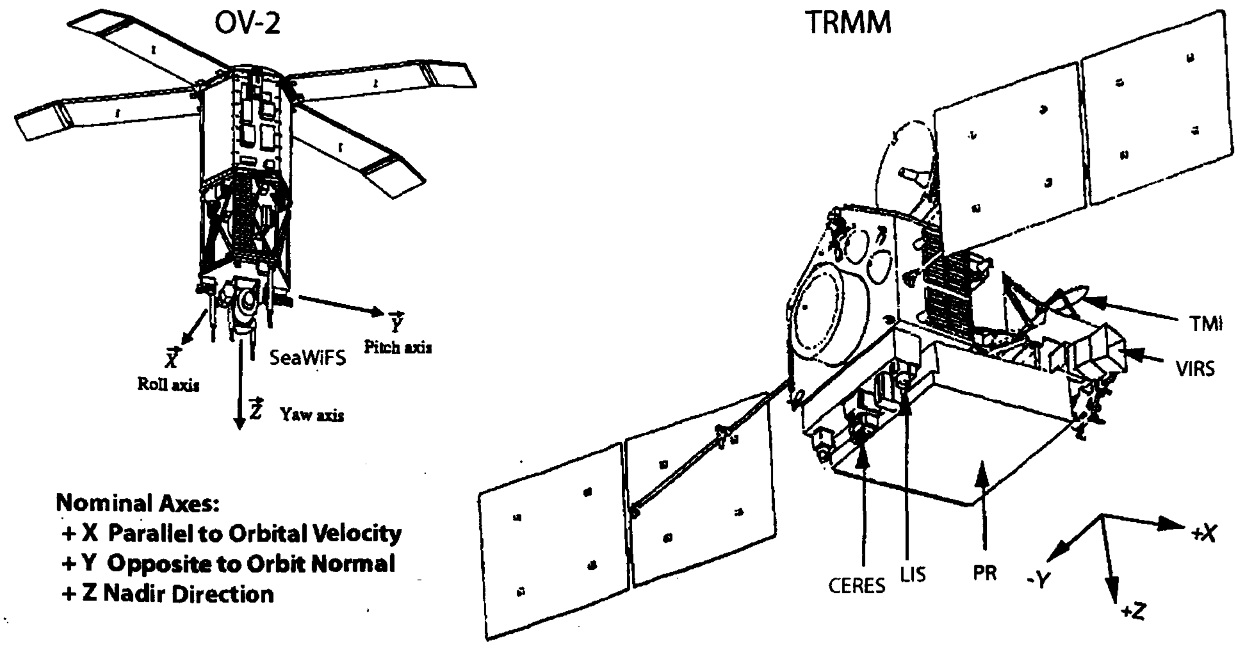

Figure 1. OV-2 and TRMM spacecraft, instruments, and coordinates.

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Table 1 OV-2 and TRMM Mission Features

Mission	OV-2	TRMM
Orbit Mean Altitude	*705 km*	*350.0 then 402.5 km after August 2001*
Orbit Inclination	*98 degrees*	*35 degrees*
Orbit Precession and Sun phases	*Nearly Sun synchronous with local noon descending node*	*-6.8 degrees/day (-6.6 post-boost) in right ascension of the node, giving about 46 day cycle relative to Sun phase in the orbit plane*
Attitude Stabilization	*Dual spin, momentum along pitch axis, magnetic coils*	*3-axis stabilized, momentum wheels on each axis. magnetic coils*
Body Pointing	*1-RPO Earth pointing spin axis near orbit normal*	*"Tip frame" from horizon bisector which is practically geodetic nadir, Yaw at 0 or 180 degrees*
Attitude Control	*Pitch controlled to zero using momentum wheel, magnetic coil commands assist nutation damping and steer momentum axis*	*Wheel control to zero pitch and roll (as computed onboard) and yaw at 0 or 180 degrees with Yaw turns every 2 to 4 week keeping +Y axis on the shaded side*
Onboard Attitude Estimation	*QUEST algorithm using noisy magnetometer Earth horizon scanner, and digital Sun sensor, data when available*	*Initially horizon sensors for pitch and roll control and yaw using gyros and Sun sensors* *After August 2001 switched to backup Kalman filter control using gyros, digital Sun sensors and magnetometers*

OV-2 Overview

OV-2 (OrbView-2, originally called SeaStar) was built and launched by Orbital Sciences Corporation on August 30, 1997 from a Pegasus launch vehicle. It carries a single instrument, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), with the primary mission of ocean color data analysis. OrbImage assumed operation of the spacecraft for commercial data sales. The mission plan included a special data buy arrangement with NASA, where the SeaWiFS project office at Goddard Space Flight Center (GSFC) and approved science users could obtain the data for non-commercial uses. The SeaWiFS project supported independent ground estimates of the orbit and attitude and extensive instrument calibrations. OV-2 is a dual-spin momentum stabilized spacecraft. The onboard attitude is computed in single frame solutions using Sun sensor, horizon scanner and magnetometer data. Ground attitudes rely on smoothed Sun sensor and horizon scanner data, and used the limited science data span over about 40 percent of each orbit, centered around the local noon descending node. The on orbit pointing performance and ground algorithms are discussed extensively in references 1 through 5.

TRMM Overview

TRMM was launched on November 27, 1997 from Tanegashima Space Center onboard a Japanese H-2 rocket. A cooperative mission between the United States and Japan, the spacecraft bus was assembled and tested at Goddard Space Flight Center (GSFC) and included 5 scientific instruments. The first space based rain radar, the Precipitation Radar (PR) was built in Japan, and other instruments built in the U.S. included the TRMM Microwave Imager (TMI), the Visible and Infrared Scanner (VIRS), the Cloud and Earth's Radiant Energy System (CERES), and the Lightning Imaging Sensor (LIS). The onboard attitude accuracy was designed to meet science requirements, thereby avoiding a need for definitive ground estimates. Ground computed definitive orbit data was provided by the Flight Dynamics Facility at GSFC. Science data products are generated at the TRMM Science and Data Information System (TSDIS) at GSFC, which supports data quality assurance. TRMM is a 3-axis stabilized spacecraft. A very significant change in the onboard attitude control was made after 3 years into the mission, associated with a boost in the operating altitude. Initially pitch and roll were controlled off of horizon scanners, while yaw was determined using the Sun sensor and propagated with gyro. After August of 2001, TRMM attitude was controlled with a Kalman filter using magnetometer and Sun sensor data along with gyro data. The onboard attitude algorithms and flight performance are discussed in references 6 and 7.

OV-2 MISSION EXPERIENCE

In this section, key modeling assumptions, performance data, and correlated error observations for the OV-2 spacecraft are presented. Control adjustments that changed overall pointing characteristics are noted, and a particular puzzle is discussed about apparent residual magnetic dipole effects. Simplified orbit period effects are considered for how certain effects may combine. Important pointing verification provided by SeaWiFS image data is noted.

OV-2 Spin Axis Stability Assumption and Roll/Yaw Coupling

As a dual spin spacecraft, OV-2 carries most of its angular momentum in its wheel, so a logical first order estimate of the dynamics is that the wheel axis stays nearly fixed in inertial space for relatively short time spans. This assumption was used in a simplified dynamics model for the OV-2 ground attitude estimation. For model simplicity, the axis was assumed to be fixed relative to orbit normal. Since the Sun synchronous precession of about 1 degree per day is small over the standard data span of 40 minutes, the simple model assumed quarter orbit roll/yaw coupling for roll/yaw state updates. The concept of quarter orbit gyroscopic roll/yaw coupling for spin-stabilized or momentum-biased spacecraft has been in common use for decades.

The spacecraft pitch axis is nominally co-aligned with the wheel spin axis, but possible misalignment effects will be discussed later. Note that OV-2 is occasionally subject to a significant amount of nutation with a period of about 5 minutes due to its dual spin gyrostat dynamics; however the nutation amplitude was kept below 0.1 degrees for most of the mission, and is not important to the lower frequency and bias effects on the pointing which are the subject of this discussion.

Coil Command Gain Reduction and Off-Orbit Normal Pointing

A key mission control adjustment was made specifically to facilitate less active motion of the momentum axis. Of particular concern were disturbances from onboard attitude errors at the subsolar point passage in each orbit. After discussion and simulation tests, the coil command (torque rod) gains for all axes were reduced by a factor of 0.25 on May 7, 1998. The positive result of this adjustment was a reduction in short-term motion of the spin axis over each data span as measured in ground attitudes and illustrated in Figure 2.

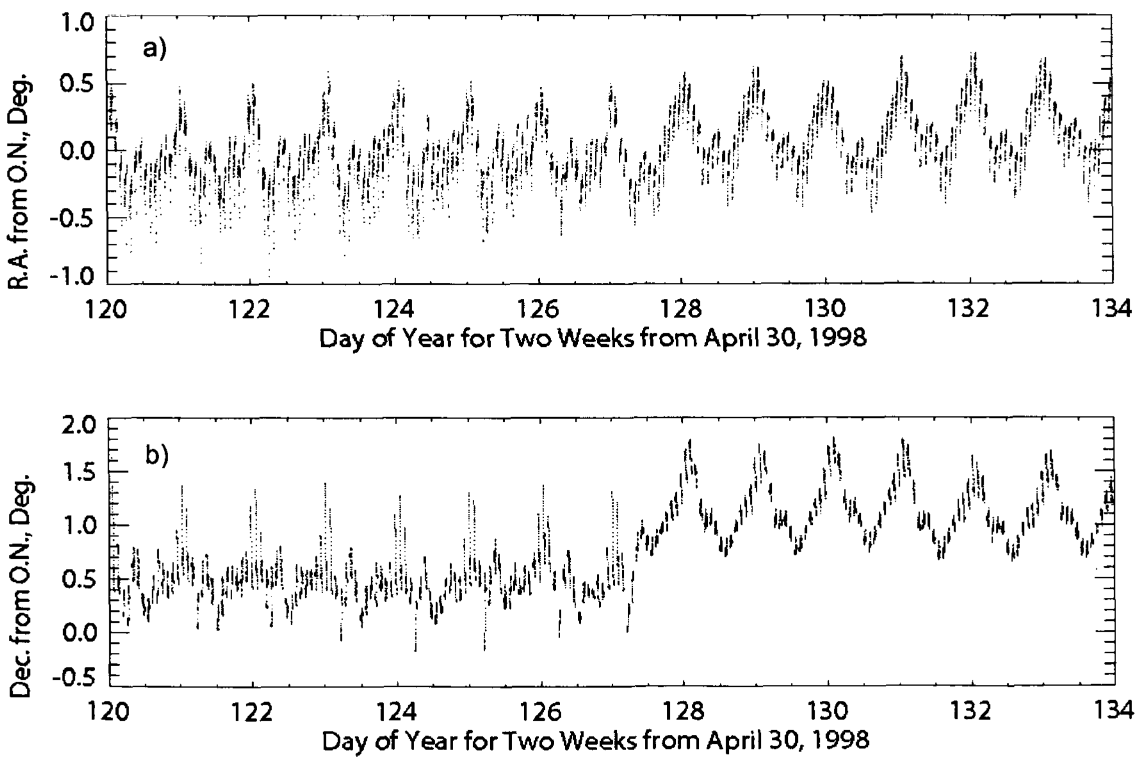

Figure 2. Change in estimated spin axis position relative to orbit normal with gain change on 5/7/98.

An unexpected result of this adjustment was that the average spin axis pointing drifted further away from the orbit normal. The reason for the off-orbit-normal bias in the pointing is not completely understood, but simulation of a residual magnetic dipole along the spacecraft pitch axis was later shown to approximately simulate this attitude drift, as discussed further after the next subsection. A possible source of some dipole bias was identified with the realization that the ground calibration for the torque rods was not actually used onboard due to a programming error, and this added about a 1 amp-m^2 Y bias to the torque commands. A proposal to correct this and add a magnetic coil command bias to compensate for the residual dipole could not be implemented, unfortunately, since it probably would have corrected the off-orbit normal pointing.

OV-2 Magnetometer Bias Adjustment Effects on Average Pointing

Another onboard adjustment that had a subtle effect on the overall pointing of the pitch axis was an adjustment of the onboard magnetometer biases. The main motivation for this adjustment was to reduce very large onboard attitude errors during the shadow period. In Figure 3 this shift is illustrated using a view of the apparent pitch axis path over representative data spans showing the range of typical spin axis positions before and after the calibration change. The apparent motion of the axis is fairly limited in each science data collection span, but shows a regular movement over the course of each day. After the adjustment, the range of motion over the day was smaller and the spin axis lagged further behind the orbit normal in right ascension. This shift was assumed to be due to changes in the average attitude steering from onboard attitude estimation errors during the backorbit period where science data is not collected.

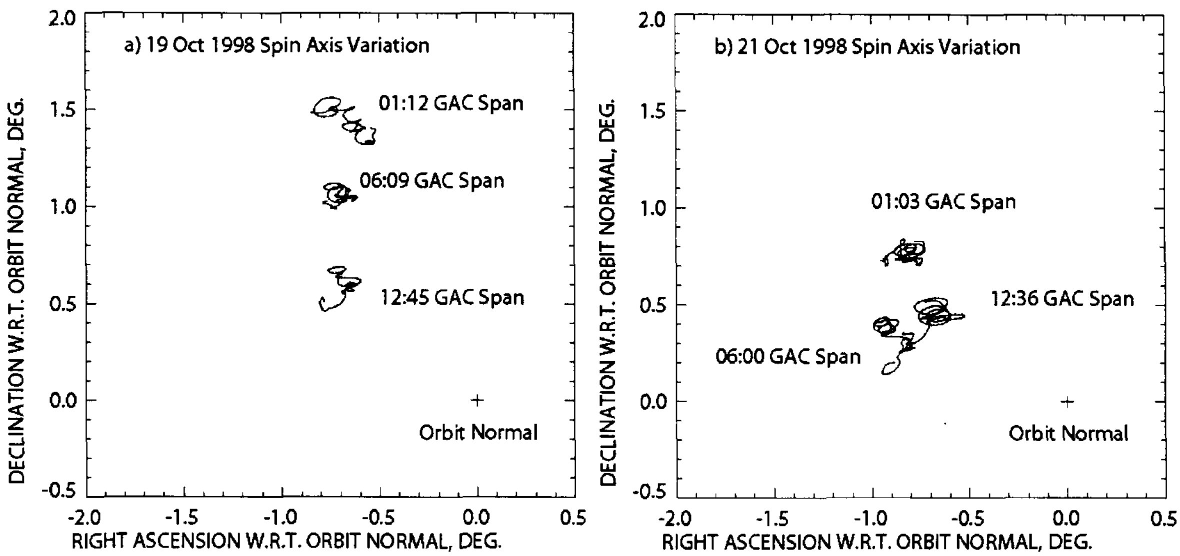

Figure 3. Estimated spin axis paths (a) before and (b) after magnetometer bias changes.

Dipole Effects from Battery Charge Regulator (BCR) Switch

In December 1998, a change in the motion of the ground calculated pitch axis was observed from an unusual and unexpected source. On December 16 1998, the spacecraft went into Safe-Haven and, after normal pointing was recovered two days later, the spacecraft Battery Charge Regulator (BCR) had switched from side A to side B. Since side A would be expected to reactivate after a Save-Haven, and it has not since, the side B change is now assumed permanent. It was later noticed that the typical attitude history over each data span had changed after this event. As roll and yaw changes these were minor; but, in terms of the presumed pointing of the spin axis, it now typically followed a looping path as illustrated by the example in Fig 4b. Such a looping path at roughly a twice orbit frequency can be indicative of a pitch axis residual magnetic dipole bias; therefore, this possibility was considered. Engineers at OrbImage indicated that the backup BCR would have an alternate external wiring path to the solar arrays, which could create a different dipole bias.

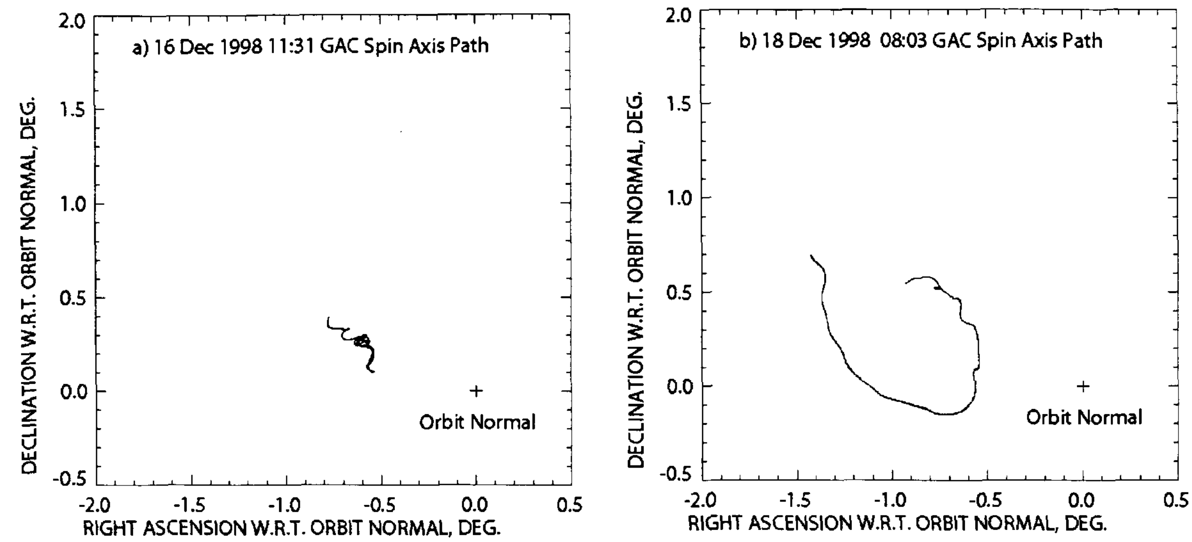

Figure 4: Estimated spin axis paths: (a) before BCR switch, and (b) after BCR switch.

Dipole Simulation and Off-Orbit-Normal Pointing and a Puzzle

While a residual magnetic dipole possibly explained more than one feature of the OV-2 pointing, it also indicated a further puzzle. In particular, a simulation of residual dipole effects with the OV-2 dynamics simulator provided an explanation for the overall off-orbit-normal pointing of the spin axis, while no other effects (like sensor biases alone) had been able to generate this behavior. A simulation over a day with a reasonable pitch axis dipole bias of 2.0 amp-meter-squared was able to reproduce general features of the pointing:

1) The looping as shown in Fig 4-b over the science observation span, and
2) The general direction of average off-orbit-normal orientation of the pitch axis, and
3) A diurnal variation in the off-orbit-normal pointing with daily roll/yaw amplitude changes

The puzzle is this: While the latter two effects were clearly present after the coil command gain reduction, the first effect showed up only after the BCR switch. A speculative explanation of this discrepancy is that perhaps a dipole had been present all along, but that it changed magnitude at the BCR switch, and initially the dipole effects were compensated for by other model adjustments that made the spin axis appear nearly inertially fixed. A change in the dipole would create the apparent motion of the measured axis just as well. We explore that speculation here briefly after some consideration of various highly correlated effects.

Some Exactly Correlated Effects—Roll/Yaw Misalignments and Constant Torque Effects

In reviewing the most basic dynamics effects from external torques it was realized that the simplest model of gyroscopic effects of constant body torques correlate exactly with reference frame misalignment effects. Specifically, there are equivalent effects from

- Body frame roll misalignment ● == ➔ Effect of constant roll torque on momentum axis
- Body frame yaw misalignment ← == ➔ Effect of constant yaw torque on momentum axis

To understand the association, one can trace the precession of the spin axis for a constant body-frame-defined torque. A torque about the roll axis along, with momentum on the pitch axis, leads to precession in yaw. As the roll axis cycles in inertial space at 1-RPO for Earth pointing, this precession causes the spin axis to prescribe a circle each orbit. The initial attitude affects where this circle starts and ends, but the phasing of the motion provides the same effect as if the body axes are shifted about the roll axis all around the orbit. An equivalent path for the body is created if the spin axis is fixed at the center of the circle, but the body reference axes on the Earth pointing part of the dual-spin spacecraft were offset about roll, *i.e.*, the body pitch axis is misaligned from the spin axis and rotates at 1-RPO. Likewise, yaw torques can provide a shift about the yaw axis around the orbit. The body frame motion is the same whether torques cause actual motion of the momentum axis or the body axes are shifted.

Note, however, with any combination of these constant roll/yaw torques or any alignment definition, there remains an axis in the body frame that will stay fixed in inertial space. It is tempting to presume that the axis that appears fixed inertially is the true momentum axis, but that might not be the case. With a perfect correlation, it does not really matter which situation is the truth (as long as the science sensors are calibrated relative to the assumed alignments to give good results). However since torques are more likely not quite constant, the effects can be expected to be only roughly the same.

Some Nearly Correlated Effects from Dynamics and Estimation

The total sum of roll and yaw torque effects can probably be expected to be nearly correlated to misalignments effects, rather than exactly correlated, because the torques will be expected to vary over the orbit due to a variety of causes. Torques come from the magnetic coil control, as well as from environmental effects such as aerodynamic and gravity gradient effects. Thus various effects contribute to the near obit frequency steering of the pitch axis.

Also, most calibration errors in any of the attitude sensors will create nearly constant offsets or variations at nearly orbit frequency or twice orbit frequency in attitude estimates. Both Sun and magnetometer measurements change at orbit frequency in the body frame, and, with the off-orbit normal spin axis, roll and roll measurements from an Earth sensor change at orbit period. Ephemeris errors can also cause near orbit frequency errors or biases in modeled reference vectors used in attitude estimation.

Further, because of the limited data span for OV-2 science data, orbit period and twice orbit period effects are more highly correlated than they would otherwise be. Consider that an orbit frequency effect could nearly have an opposite influence to a twice orbit period effect within a short span, as discussed in the next subsection.

Ideal Twice Orbit Period and Orbit Period Error Combination Over a Short Data Span

A pitch axis dipole creates a generally twice orbit period looping path for spin axis motion in inertial space, although the rates are not truly uniform around the orbit as the magnetic field direction and magnitude varies unevenly around the orbit. Nevertheless, for simplicity of illustration here, an ideal twice orbit period motion as seen over a limited data span will be considered. While OV-2 science data is collected over about 40 percent of an orbit, a twice orbit period path of the pitch axis with 1 degree radius of motion would appear as illustrated in Figure 5a. Meanwhile, the effect of a 1.2 degree offset in yaw on the assumed body pitch axis will cause the offsets shown in Figure 5b. The sum of these two effects give this assumed pitch axis's motion as shown in figure 5c. The looping paths in Figures 5d and 5e show a similar sum for other assumed pitch axis offsets in yaw of 1.5 and 1.8 respectively. The family of paths in 5c, d, and e all represent possible signatures for various body axes near (but not co-aligned with) the wheel spin axis (+which is prescribing a twice orbit period path in inertial space). These body axes are not fixed inertially, but show less motion than the wheel spin axis.

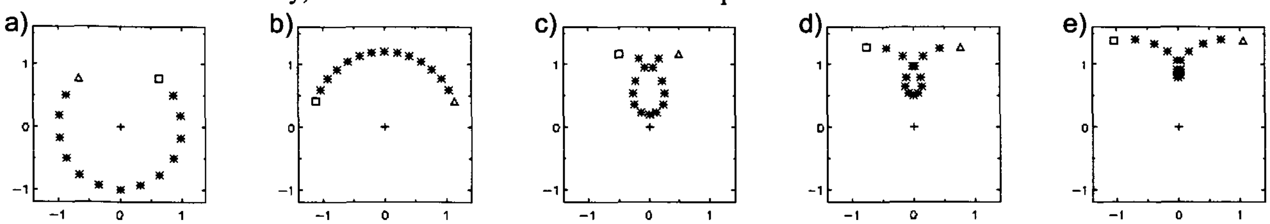

Figure 5. Paths over 140 degrees of orbit for a) twice orbit period motion at radius 1, b) Yaw offset at 1.2, c) Sum of (a) and (b) offsets, d) Same as (c) but with 1.5 offset, and e) same as (c) but with 1.8 offset. Triangles indicate start and boxes indicate end of described axis paths, with asterisks at 10 degree increments. The horizontal and vertical plot axes represent right ascension and declination relative to orbit normal (marked by + symbol).

Previously, we speculated: Could it be that the early mission dipole effects were compensated by other model adjustment in making a nearly stationary axis? The family of paths in 5c, d, and e are good starting points for considering various other error effects that, perhaps in combination, could result in even less motion observed for some selected body axis, even though significant dipole induced precession is actually present. Adjustments to the apparent paths could be created by various estimation errors, or adjustments to the real paths can be created by dynamics refinements. Basically we want to identify some effects that bring the axis declination up in the middle of the span, especially for the axis path in 5c; and/or bring in the right ascension "wings" at the beginning and end of the data span, especially for the axes paths in 5d or 5e.

How Time Dependent Yaw Errors Can Make an Axis Away from the Spin Axis Appear Stationary

We will discuss the estimation error possibilities first, which turn out to have limited viability in this case, but which can help us visualize the magnitude of the adjustments needed. We can ask, what exact yaw error versus orbit angle could combine with the twice orbit frequency pitch axis path (over 40 percent of the orbit) and appear to keep one body axis fixed in inertial space? This turns out to have an elegant solution, at least in planar approximation: a yaw error magnitude that varies as the cosine of θ, where θ is the orbit angle from the middle of the data span as illustrated in figure 6a and 6b. The vertical line in 6a and the radial lines in 6b illustrate the adjustment relative to a constant yaw offset (with effect similar to 5d by itself), as we are changing the magnitude of the yaw adjustment with time. We arrive at an apparent path that exactly mirrors the spin axis path with a displacement. The right angle triangle inscribed in the dotted line semi-circle illustrates why this formula works. A yaw error effect need not be exactly like this, and yet could still make the apparent pitch axis motion quite small. For example the symmetric straight line segment yaw errors also shown in Fig 6a would make the small multi-looped path in figure 6c. Also note that the smoothing performed in the ground attitude would smooth out any small loops of apparent motion of this axis.

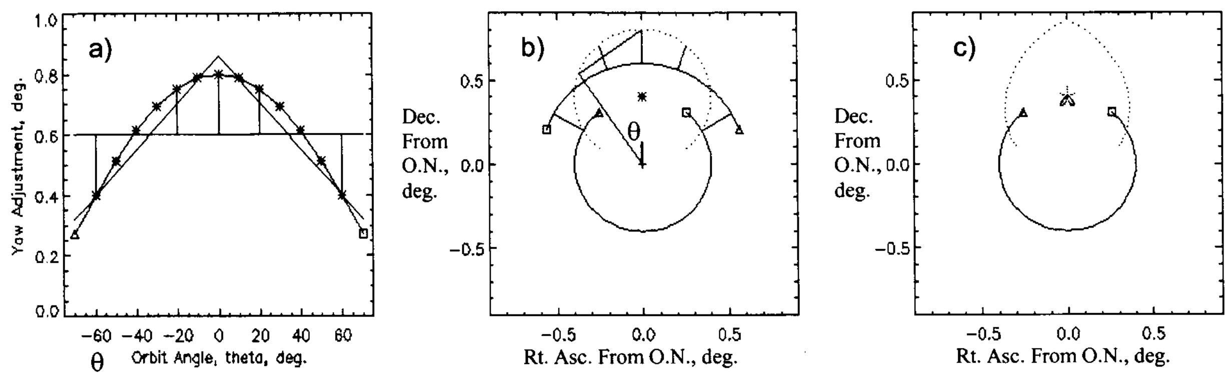

Figure 6. Yaw error versus time to create apparent fixed axis with twice orbit period motion loop. a) suggested error functions versus orbit angle theta, θ, b) cos(θ) error form relative to constant error brings axis to new point, and c) line segment error function brings axis in with very small motions. See text for description.

An attitude estimation error contrived like this is probably not the reason for an apparently fixed axis in the presence of a dipole bias for two important reasons. First, it is important to note the estimation error effects are qualitatively different than dynamics effects or alignment reference selection in that they only create an apparent, not true, axis stability. An axis that is assumed stationary, but is not actually, would misrepresent science instrument pointing. Fortunately, an extensive verification of the instrument pointing is implemented for SeaWiFS by automated checks of island targets, so we believe our systematic errors are limited to less than about 0.1 degrees generally. Second, it seems that the functional error form we are looking for does not match patterns from island target residuals, which vary with season. Different error patterns would be expected from systematic error effects that we've considered likely sources, like horizon radiance effects or errors from misalignments interacting with Sun-Earth geometry around the subsolar point in the orbit. Nevertheless it is still possible that systematic errors contribute somewhat to axis estimation errors, especially in the middle of the data span which has limited yaw observability, and at the ends of the data spans where there turns out to be many fewer island targets available for providing pointing verification. For example, roll errors that change sign on the two ends of the data span can bring in the wings of paths 5d or 5e. Also attitude estimation filtering effects would reduce the apparent motion at the ends of the data span as well

How Additional Dynamics Effects Can Make an Axis Away from the Spin Axis Appear Stationary

It seems a more likely cause of an inertially fixed axis shifted from the spin axis would be from additional dynamics effects, and torques that might do this can be readily derived from the functional yaw error form discussed above. With the pitch momentum bias, roll torques will generate yaw motion, and the functional form needed is given by the derivative of the contrived yaw error functions. Therefore, the ideal fixed axis requires a roll torque that changes as the sine of the orbit angle theta. The dipole effect is twice orbit frequency in inertial space but once per orbit frequency in the body frame. The additional torque suggested acts at once per orbit frequency in the body frame to counteract part of the dipole effect and make the overall torques constant in the body frame for our data span. This, as discussed, gives the equivalent effect to an axis shift. This exact torque pattern is not needed for very limited axis motion. For example, the motion in Figure 6c could also be generated by a constant roll torque that simply switches sign at the middle of the data span.

It thus seems possible to keep an axis, one that is a bit offset from spin axis, approximately fixed over the science data span even though overall a significant dipole affects the off-orbit normal pointing. It would appear more direct to just assume that there really was no significant dipole bias present prior to December 16, 1998, and other effects that are not yet understood drove the overall pointing away from orbit normal. However, the true dynamics are undoubtedly more complicated. Note that since the BCR dipole source may be from wiring paths to the solar arrays, it might create a time varying dipole only in sunlight. Further, a main source of torques is from onboard control system, which is designed to maintain the pitch axis pointing and overall momentum. Our simulation may not well represent various details of the true dynamics, and it is apparent we don't have complete understanding of all the effects on the spin axis attitude drift. To pass along a favorite quote among OV-2 ACS support engineers, "there's some kinda dynamics going on."

Can One Effect Cover For Another?

High correlation in two model effects is often harmless, as one bias parameter can compensate for another. Potential biases cannot always be separately observable, but as long as an adequate calibration reference assures that key data, *e.g.* science imaging data, is regularly on target, any sources of constant alignment-type offset are compensated in aggregate. It does not matter which axis of the spacecraft we are tracking, as long as we track it accurately enough, and have the correct alignment with our science sensor. However, if one modeled error will not exactly compensate for another one with slightly different effects over time, this leaves uncertainty. One needs to consider how consistently they match, and what changes in the environment might bring out different effects on the attitude.

Island Targets' Value for Verification

The SeaWiFS project supported extensive verification of the science instrument pointing by automatically calculating errors of island locations in the image data, typically catching 100 to 200 island targets per day in the routine data (ref 3). This data was used in the refinement of the attitude calibrations, as well as for continuing quality assurance, which is important for verifying that errors are not accumulating or biases changing.

Noise in the island target position measurements mean that they mainly provide an overall verification from statistical averages on a coarse time and space scale. Attitude errors are calculated from this data in 10 degree latitude bands on a monthly basis. This is invaluable in catching any systematic bias-type shifts. However, these checks would not generally catch short-term excursions in the attitude, and the OV-2 control system is susceptible to various occasional glitches (ref. 1), and does not have gyros or an accurate dynamics model to reliably track through these events. Also, it is important to note the limitation that there are few island targets available below 50 degrees south latitude or above 70 degrees north latitude, and this may contribute to more uncertainty in our calibrations on the ends of the data spans.

But What If Something Changes the Environment? Warnings!

Concerns with any modeling arise particularly when something about the mission geometry or dynamics changes. Then one modeled effect may not compensate for the actual errors as it did previously, and new errors can be introduced. The ground attitudes for OV-2 have proven rather robust because they have been verified through a range of changing conditions. Nevertheless, there is a concern with the effects of the BCR switch, and one other environment change is noted for future data.

After the BCR switch, the onboard Kalman filter needed to track more motion due to the looping path in the pitch axis, and it is expected and shown by some simulations (ref. 4) that this tracking would have some errors. It is known from the attitude sensor geometry that there is limited yaw observability through the subsolar point, and the estimates will tend to take a shortcut on the looping path. This can cause yaw errors of 0.1 to 0.3 degrees around the subsolar point depending on the filter tuning. An effort was made to model the looping path in the dynamics and it did not seem to make noticeable difference in the attitudes. The limitations of the dynamics model are somewhat compensated by the two-directions Kalman smoother used for ground processing. Therefore, this was not a big concern for OV-2 ground attitude estimation, at least for the level of motion witnessed. Nevertheless it should be noted this type of change can affect attitude estimation accuracy.

As the OV-2 mission is extended, it is expected that the orbit plane will drift significantly away from the local noon descending node, as it is doubtful that OrbImage can or will support an orbit adjust. This means that the Sun sensor will start operating over parts of their fields-of-view that have not been routinely used, or calibrated. This should not be a problem, but it is another example of a change in the environment where one may consider whether calibrations under previous conditions apply.

TRMM MISSION EXPERIENCE

The TRMM spacecraft switched attitude control modes with the orbit boost in August 2001. Originally the contingency Kalman filter control mode was only intended to meet a degraded attitude accuracy of 0.7 degrees; however after correcting some prediction errors in the onboard ephemeris and adjusting an onboard magnetometer calibration matrix, it proved possible to meet the original 0.2 degree accuracy requirement after the boost. Attitude checks using science instrument data helped with pointing performance review after the boost, and we have now also looked a bit at what this data shows about the pre-boost pointing. We show data indicating overall bias shifts after the control mode switch. Then various correlations in the post-boost attitude errors are discussed, with some curious similarities with OV-2 pointing noted. The control is much smoother in the Kalman filter mode, but is susceptible to orbit frequency roll/yaw errors.

Pre-Boost Control Using Earth Horizon and Gyro-propagated Yaw Updated By Sun Sensor

Prior to the orbit altitude boost, pitch and roll were obtained directly from the Earth Sensor Assembly (ESA). The most noticeable short-term error to which the ESA was susceptible was occasional Sun or Moon interference in one of the four quadrants. During predicted interference periods, the ESA was switched to 3-quadrant control, and this occurred over several days each month. Yaw was updated twice each orbit using data from each of the two Sun sensors, with gyro data used for yaw propagation. A sample span of the onboard reported roll, a PR data derived roll, and an approximate ground computed gyro-propagated roll angle is shown in Figure 7, which includes one of the larger disturbances from Sun interference effects.

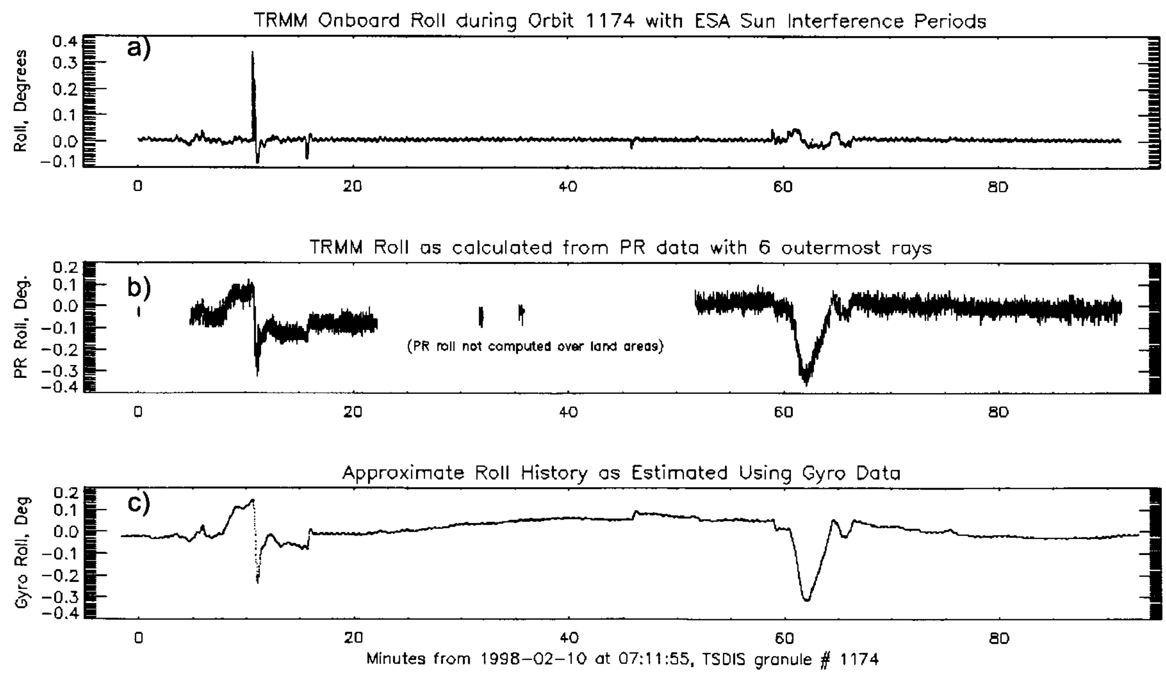

Figure 7. Sample roll estimates for pre-boost early mission orbit a) onboard, b) from PR, and c) from gyro.

Since the control keeps the attitude close to the onboard estimate, the onboard reported attitude is practically always close to zero. Only sudden jumps in the estimated roll show up as spikes in the reported attitude, and the control quickly responds, within tens of seconds, to null the pointing. Figure 7b gives an estimate of the roll from the PR science algorithm estimates of the surface echo distances. Roll was proportional to the difference between the left and right sides of the scan in the average distance to the surface echo over sea surfaces (ref 8).

The third plot shows the roll error history as approximately estimated using gyro data with nominal calibrations. The gyro data tracks the short-term variations very well. However, this estimate has uncertain orbit frequency errors that depend on the initial attitude, which is not accurately known. Nevertheless, the gyro data is useful to show that the roll error reported from the PR data is basically on track with the gyro-calculated motion to within its noise levels.

Post-Boost Control Using Kalman Filter with Magnetometer, Sun Sensor, and Gyro Data

After the orbit altitude boost, all three axes were computed with the Kalman filter, using Sun sensor and magnetometer data, and gyro data for attitude propagation. Since the attitude propagation is very smooth and reliable with the gyro data, the only motion shown in the onboard reported attitude are very small disturbances from solar array and antennae motions. A sample span of the onboard reported roll in the post boost period is shown in Figure 8a. The small disturbances are from array motions at shadow entry/exit and high gain antenna motions. The roll data shows a smooth sine wave pattern. A gyro propagated roll history is not shown with Figure 8, but we note it could look exactly like the onboard roll or could show a sine-wave roll history also, depending on the initial attitude. Independent ground-computed attitude estimates by the Flight Dynamics Facility showed similar sinusoidal roll errors, with uncertainties on the order of a tenth of a degree using an orbit or two of data.

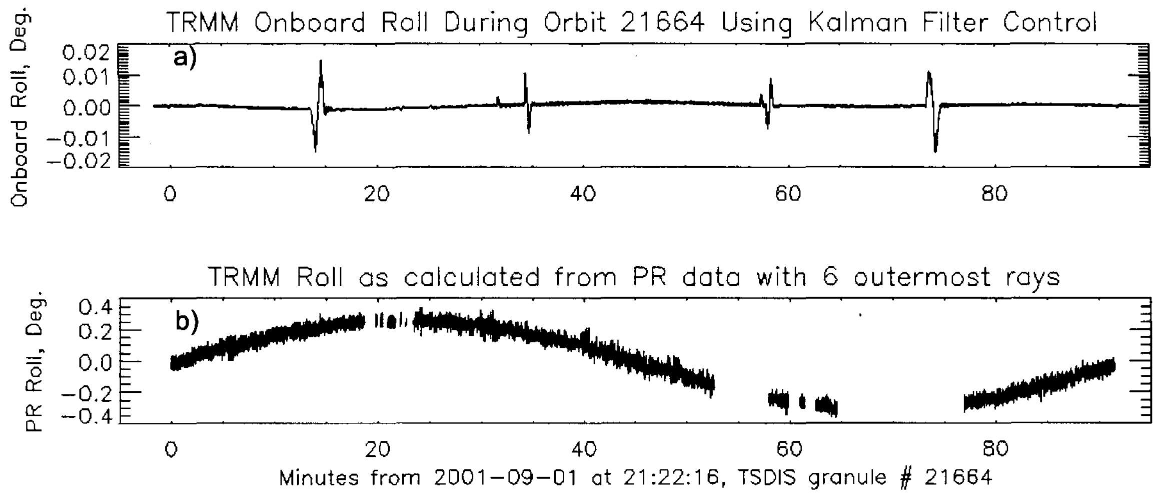

Figure 8. Sample roll estimates for orbit under Kalman filter control, a) onboard, and b) from PR.

Roll/Yaw Coupling in Kalman Filter Attitudes – PR Rotation Axis Off-Orbit-Normal

The orbit period sine-wave pattern for the roll was seen in every orbit examined, so it was quickly realized that this pattern should be expected for attitude propagation with gyro data. The control system by design keeps the spacecraft at zero pitch, roll and yaw as determined by the Kalman Filter. This means that the control system is having the body rotate basically at 1-RPO about the body pitch axis. This is analogous to the inertial pointing spin axis discussed for OV-2, though not precisely the same. The TRMM orbit precesses about -6.7 degrees per day in right ascension of the ascending node, or about ½ degree per orbit, but the control system tracks that motion using the onboard ephemeris information. The fact that TRMM points at the geodetic nadir (onboard 'tip' frame) means that the pitch axis is not actually fixed relative to inertial space and varies a few tenths of degree in declination, but that effect is not seen in the radar measured roll, which is also relative to a geodetic nadir. The net effect of errors in the initial attitude are orbit period roll and yaw variation, with yaw leading roll—the same type of quarter orbit coupling seen with the inertially fixed spin axis. We can think of the PR data sine wave as specifying an average, effective "PR rotation axis" that is offset from orbit normal by the amplitude of the maximum roll error.

Systematic Error Shifts with Control Mode Switch

Most science data users are unlikely to notice small attitude errors, but one user of TMI Data, Frank Wentz, was the first data user to notice changes in post-boost science product attitude accuracy. His use of the data for Sea Surface Temperature (SST) measurements is sensitive to the incidence angle of the TMI passive microwave observations. By fitting the SST residuals from an independent SST model, he and Chelle Gentemanm estimated biases and orbit period errors in pitch and roll on an average daily basis. The pitch and roll bias results leading up to and beyond the orbit boost are shown in Figures 9a and 9b. Since there is an important change in the TMI instrument scans after each yaw turn, the data here is color-coded; when TRMM has the -X axis forward (and TMI scans right to left behind the flight path, rather than left to right ahead) the data is coded red. There is a clear shift in the error patterns after the control mode change, and clear seasonal patterns in roll before the control mode change.

We also computed an average roll bias for each orbit using PR data, and that plot is shown below the TMI Roll Bias (with some data gaps), on the same time scale but marked in years from January 1, 1998. Our plot, unfortunately, had data gaps and is not color-coded for the yaw orientation +/- 180 degrees. However the measurement of this roll bias pattern from two independent sources gives confidence that these offsets are real.

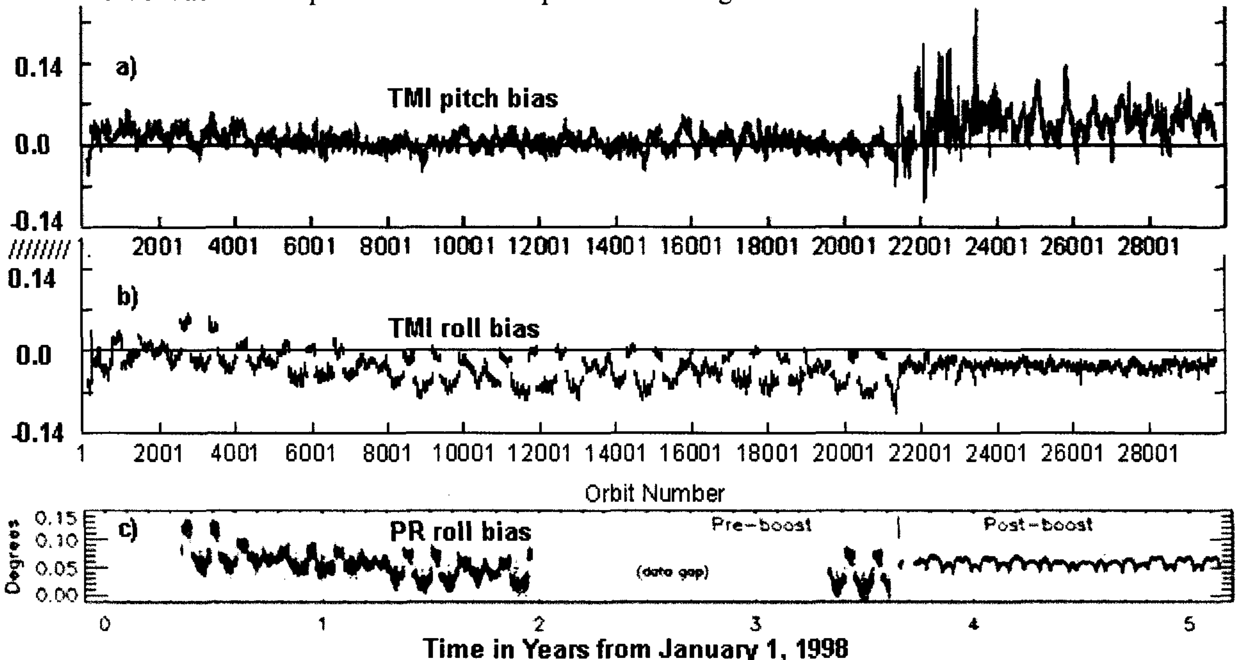

Figure 9. Bias estimate for a) pitch from TMI, b) roll from TMI, and c) roll from PR data.[†]

The annual variations in roll before the control mode change shift magnitude with each yaw turn of TRMM. Since systematic horizon radiance variations would be expected based on past mission experience to provide a source of roll error from any horizon sensor, the TRMM Earth Sensor Assembly (ESA) would be expected to drive this type of seasonally changing roll bias. The summer to winter pattern change is best seen in the time history in one color on Wentz's TMI Roll bias plot. The main radiance effect is a north-south horizon height gradient that shifts sign with seasons. The horizon appears higher toward the summer hemisphere. After the control mode change the average roll bias is much more stable. Possible post-boost correlation with gyro biases is noted below.

The average daily pitch bias shifted after the boost, and was significantly noisier. Some contributors to the Kalman filter pitch uncertainty include ephemeris errors and coupling to roll/yaw errors, as discussed below. There are no significant seasonal variations like those found in roll. What might be expected in pitch from horizon radiance effects are twice orbit period errors, but these are expected to be smaller than the roll errors.

Some Exactly Correlated Effects under Kalman Filter Control—Gyro Biases and Roll/Yaw Misalignments

In considering the effect of gyro biases on the attitude under the Kalman filter control, there are analogous effects to the correlations between misalignments and constant torque effects on spin stabilized spacecraft. Specifically, we have equivalent effects from

- Body frame roll misalignment ● == ➔ Effect of constant roll axis gyro bias
- Body frame yaw misalignment ● == ➔ Effect of constant yaw axis gyro bias

Since the dominant rotation of the spacecraft is 1-RPO about the pitch axis, small biases from gyros on the other axes effectively just offset the gyro-calculated body rotation axis. If the system is controlling based on a different

[†] TMI pitch and roll bias estimates provided courtesy of Frank Wentz of Remote Sensing Systems.

roll or yaw gyro bias, it will rotate about an axis offset in roll or yaw respectively, shifted by the vector addition of the bias to the 1-RPO pitch rate. If a roll or yaw gyro bias is added instantaneously starting from zero pitch/roll/yaw it creates a coupled orbit period roll/yaw signal, since the spacecraft is suddenly effectively rotating about an axis shifted from orbit normal. However if a attitude is chosen to put that new rotation axis directly along orbit normal, the body frame is left with a constant roll or yaw offset bias respectively.

Onboard Ephemeris Error Effects on Kalman Filter Earth Pointing Frame

After the switch to the Kalman Filter, the sensitivity of the pointing control to the onboard ephemeris became a concern. In the previous control using the horizon scanners to maintain Earth pointing, ephemeris errors were of little concern and only affected TDRSS antennae pointing slightly. Now, with the filter use of only Sun sensor and magnetometer data, the information needed to maintain Earth pointing is computed onboard with the available ephemeris (by providing the inertial to orbital coordinate frame transformations). On September 28, 2002, the onboard along-track error reached as high as 80 kilometers after a delayed uplink of the new Extended Precision Vector (EPV). This gave about 0.7 degrees error in pitch just from the onboard coordinate frame errors. In addition to the direct coordinate frame effects—which mainly affect pitch for typical along-track errors—there are secondary effects from the onboard magnetic field model taken from the wrong place in the orbit and coupling to roll/yaw errors, which will be discussed later. The along track errors for about 200 days beyond the boost are shown in Figure 10a based on differences between the onboard and the ground-computed definitive ephemeris.

TRMM Post-Boost Roll Error Tracking Using Radar Data

Relying on the observation that an orbit period sine wave is expected in roll, a trending effort was established to fit the amplitude, phase, and bias of the orbit period signal in the PR computed roll from each orbit. These values turned out to be very stable from orbit to orbit and show various diurnal, Sun angle, and longer period patterns. The Sun elevation from the orbit plane, known as the solar beta angle, showed particular associations with this data after the boost, so that is shown plotted in Figure 10b. Where the beta angle passes through zero is where the yaw turns take place. The main item of interest to science users after the boost was the maximum roll error each orbit, *i.e.*, the amplitude of the sine wave fit, and this is shown in Figure 10c.

The phase of the sine wave in each orbit changed gradually at a rate associated with the precession of the orbit plane relative to the Sun. Therefore, the phase relative to the Sun direction was considered in further analysis.

PR Rotation Axis Offset Patterns relative to the Sun Direction

It was found that the phase in the orbit of peak roll errors tended to be plus or minus 90 degrees from the Sun direction in the orbit plane. This can be interpreted to say that the PR rotation axis location tends to be offset in a direction in inertial space generated by a rotation about the sunline. The offset of this axis relative to the Sun direction is shown in Figures 10d and 10e, and shows that indeed most of the drift in the PR rotation axis away from orbit normal is perpendicular to the Sun direction. The variations are an order of magnitude larger perpendicular to the sunline. This makes sense because this is the direction that keeps the same Sun angle from the pitch axis, and the Sun sensor is the most accurate sensor. The very small amount of variation in the PR rotation axis toward the Sun direction seems to correlate to the yaw position (+X or –X forward) and the solar beta angle.

TAM Matrix Updates and Attitude Improvement

After the boost, the attitude pointing was less accurate than hoped for, and the magnetometer calibration was suspected. New calibrations that were computed did not show significant change from the previous calibration, and their uplink (*1 as noted on Figure 10c) did not change the performance. Further investigation uncovered an error in how the magnetometer calibration information was used onboard. The onboard computations effectively presumed an orthogonal alignment matrix so that the transpose could be taken as the inverse, while the ground computed matrix allowed scale factor and non-orthogonal axis adjustments. A decision was made to uplink the transpose of the inverse of the ground-computed matrix so that more proper magnetometer residuals would be used onboard. This was done on November 28, 2001 (*2 as noted n Figure 10c) and led to improved performance. The overall improvement in attitude trend shows most clearly in the PR rotation axis offset perpendicular to the Sun (Figure 10d). Ignoring temporary effects from ephemeris errors and yaw turns, there seems to be a slow but regular drift toward a point 0.2 degrees on one side orbit normal until after this correction.

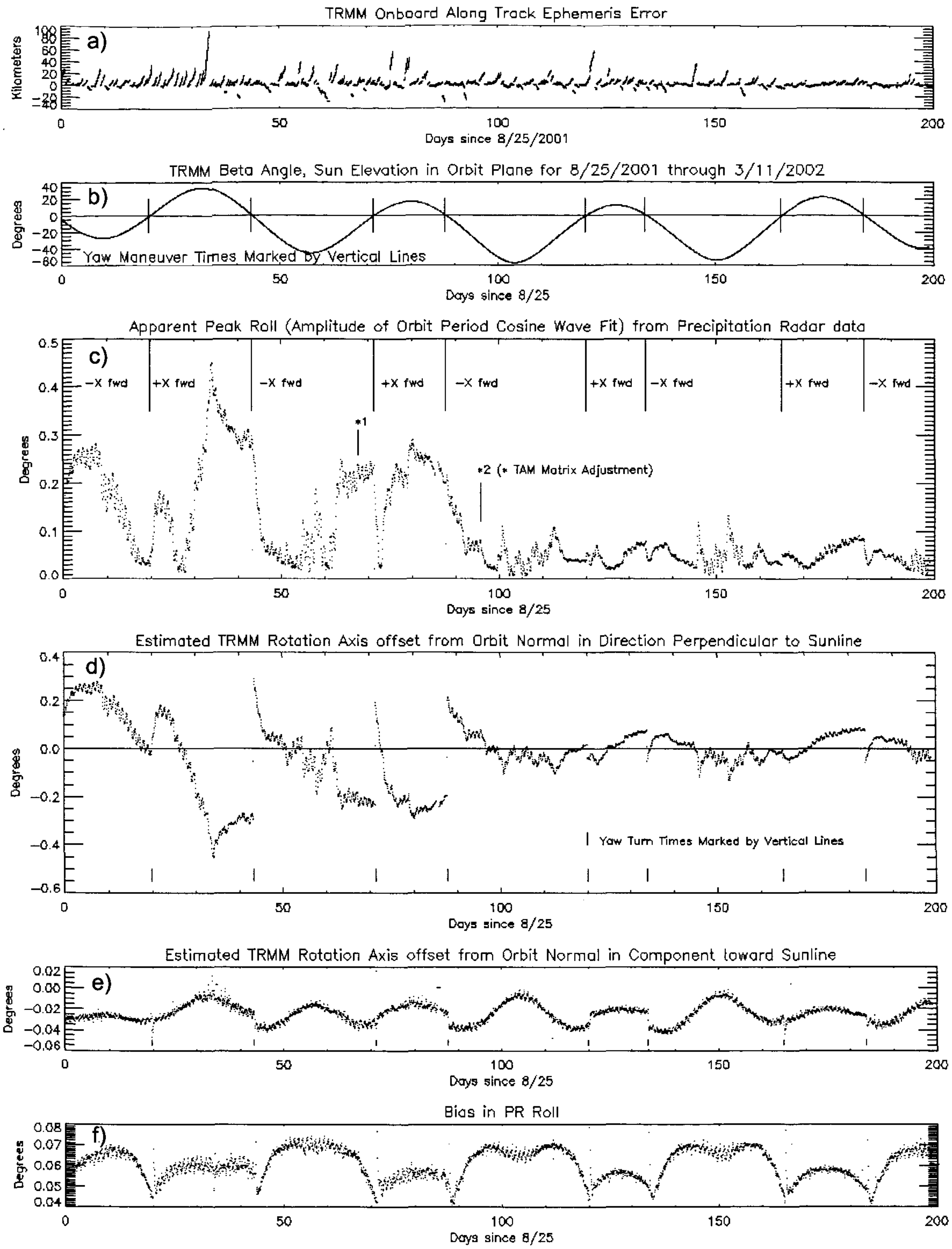

Figure 10. TRMM ephemeris error, beta angle, and Kalman filter attitude error trends tracked using PR data.

Post-Boost PR Bias Patterns

The average offset in the PR bias is understood to be due to the roll alignment offset between the PR and the onboard attitude references frame. The bias has a small time varying amplitude that is also loosely correlated to the solar beta angle. A natural suspected source for this pattern is Sun sensor calibration errors that change effects across the field-of-view with beta angle change. There is also a noticeable change in the bias after each yaw turn for a few orbits. This is probably associated with the settling of the gyro biases, since an expected correlation of the roll bias to roll-axis gyro biases has been noted. The yaw gyro biases tend to settle at different values after each yaw turn. More might be learned by detailed comparison with TMI SST estimated roll bias. The gyro bias correlation with roll offsets for TRMM could merit further study.

Roll/Yaw Coupling to Pitch Versus Beta Angle

When the orbit period roll and yaw errors are present, this can lead to a systematic bias in the spacecraft pitch depending on the solar beta angle. This was realized only after examination of residual pointing errors with a manual check of a few island targets after adding other known corrections, however the case for this effect can be understood from the geometry. We showed how an offset by a rotation about the sunline (essentially in inertial space) generates the orbit period roll and yaw. It is important to note that a rotation about a sunline also changes the spacecraft pitch by an amount that varies as the sine of the beta angle, as illustrated in Figure 11.

The pitch and roll/yaw error amplitudes are tied together by the Sun measurements, *i.e.* by maintaining low Sun sensor residuals. The rotation about the sunline maintains the same Sun angle from the pitch axis for the path it takes in the body frame. That keeps one direction of the Sun measurement residual errors small, but the other direction, associated with the phase of the Sun in its path in the body frame, must be accommodated by a pitch adjustment.

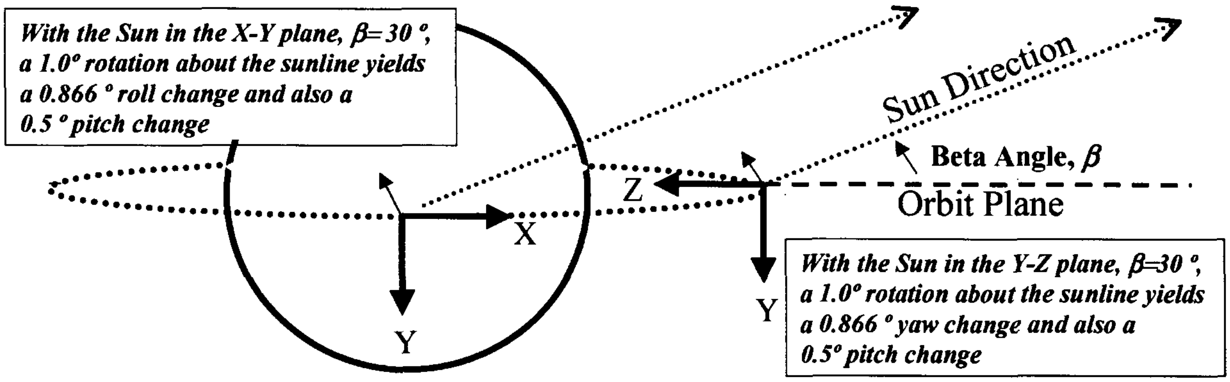

Figure 11. Schematic illustrating pitch coupling to roll or yaw for rotations about Sun direction.

Pitch offsets associated with the roll/yaw orbit period errors were noted in simulated data for the original Kalman filter contingency mode design studies (ref. 6) and it was reported that this effect was seen in other spacecraft, e.g. UARS and SAMPEX. This effect was also seen in recent re-entry simulations for TRMM. So presumably this effect is taking place onboard TRMM, although we currently have very limited visibility in flight data to verify the effect is taking place.

Ephemeris Errors and Roll/Yaw Errors from Pitch Errors

It seems that this coupling could be what allows onboard ephemeris errors to lead to roll/yaw errors. Evidence is given by the empirical observation that onboard along-track errors lead to the PR rotation axis offsets only when they occur during high beta angles. The direct effect of along-track errors, discussed above, leads to pitch errors for the computed Earth pointing coordinates. The coordinate error will create residual errors in the Sun measurement, and a pitch adjustment that, when tied to a rotation about the sunline by the Sun observations, leads to a coupled roll/yaw adjustment.

Independent Instrument Pointing Verification by Spot Checks of Images

In addition to the specialized pointing checks with PR roll data, and TMI SST data, occasional spot checks of image data have been done against coastline maps for the three TRMM imaging sensors. This is important because ultimately each of these could have misalignments of their own on any axis. However, visual spot checks only verify pointing to about half of a pixel, and it is prohibitively time consuming to generate statistical results showing overall biases and average accuracies versus latitude or position in the scan as has been done with the SeaWiFS island target checks. Thus, we currently have only a coarse ground verification of alignments, and evidence of some systematic offsets in the quarter to half pixel range. On the other hand we do have the advantage on TRMM that the gyro data can generally track the attitude motion well with the Kalman filter mode, so if the pointing is verified for a good number sample points, it probably does just as well at times in between.

Another Environment Change, TRMM Reentry Simulations and Another Puzzle

A possible future operating environment change that has been given consideration recently is the possible controlled reentry of the TRMM spacecraft. This has raised interesting questions regarding correlated errors in the reentry environment. TRMM has not heretofore been flown in a highly elliptical orbit. Simulations of the re-entry with the flight software and the Hybrid Dynamics Simulator mysteriously showed slowly growing orbit period roll/yaw and pitch offset errors. Gyro biases also show some smaller tendency to drift. This may just be due to as-yet-unidentified simulation modeling problems that would not happen in real flight, however it may be an indicator of sensitivity of the real pointing to relatively small modeling errors. In flight, there are environmental unknowns associated with the reentry. For example, the magnetic field strengths are larger at low altitudes, so the magnetometers will operate over a new range of measurements. Also there will be stronger magnetic coil commands to counteract drag at lower altitudes and this might cause orbit frequency errors in the magnetometers. Calibration errors covering the new range of measurements could lead to pointing errors. Possible effects on the attitude performance deserve careful study. To paraphrase the observation about OV-2 dynamics, there are "some kind of correlations going on" that might need to be better understood.

CONCLUSIONS

With changes in the attitude control environment for two Earth-pointing spacecraft, we've discussed various correlated error effects that are of concern. For the OV-2 spacecraft, it was shown how some axis offsets, estimation errors, or dynamics effects could have made an axis appear stationary while residual magnetic dipole dynamical motion is present overall. Details of the dynamics and active control are not well understood, but extensive ground calibration with island targets limits the likelihood of systematic estimation errors.

For the TRMM spacecraft, some aspects of the pointing performance have been verified by using science instrument data. Occasional Sun interference effects give the largest errors in the pre-boost period. The mode switch exchanged occasional short-term interference and systematic radiance effects from the horizon scanner for much smoother control with orbit period errors. Offsets of the rotation axis tend to occur perpendicular to the Sun direction, with coupled pitch errors under Kalman filter control Overall pointing accuracy for each sensor is still limited by image alignment errors in the half-pixel range.

Analogous behavior has been noted between the roll/yaw quarter orbit coupling for a spin-stabilized spacecraft and for a three-axis stabilized spacecraft under Kalman filter control. Also constant roll/yaw torques on a spin-stabilized spacecraft have similar effects to a constant roll or yaw gyro bias under Kalman filter control.

REFERENCES

1. Bilanow, S. and F.S. Patt, "SeaWiFS Postlaunch Technical Report Series Volume 28, Pointing Performance for the SeaWiFS Mission," NASA/TM-2004-206892, Vol. 28, NASA Goddard Space Flight Center, March 2004.
2. Bilanow, S., F. S. Patt, and S. Kennison, "Atitude Sensor Bias Evaluation for OrbView-2," NASA/GSFC Flight Mechanics Symposium NASA/CP-1999-209235, Greenbelt, MD, May 1999.
3. Patt, F. S., and S. Bilanow, "Attitude Sensor Alignment for OrbView-2 Using Island Targets," NASA/GSFC Flight Mechanics Symposium NASA/CP-1999-209235, Greenbelt, MD, May 1999.
4. Bilanow, S. and Patt, F.S., "Dynamics Effects on SeaWiFS Pointing Errors," In-orbit Geometric Characterization of Optical Imaging Systems, Bordeaux, France, November 1999.
5. Patt, F.S. and Bilanow, S., "Horizon Scanner Triggering Height Analysis for OrbView-2," NASA/GSFC Flight Mechanics Symposium NASA/CP-2001-209986, Greenbelt, MD, June 2001.
6. Crassidis, J.L., S.F.Andrews, F.L. Markley, and Kong Ha, "Contingency Designs for Attitude Determination of TRMM," NASA/GSFC Flight Mechanics Symposium NASA/CP 3299, Greenbelt, MD, May 1995.
7. Andrews, S. F. and Bilanow, S., "Recent Flight Results of the TRMM Kalman Filter," AIAA Guidance Navigation and Control Conference, AIAA 2002-5047, Monterey, CA, August 2002.
8. Kwiatkowski, J., S. Bilanow and J. Stout, 2002. Estimating TRMM Spacecraft Attitude Errors Using the Precipitation Radar. IEEE International Geoscience and Remote Sensing Symposium, Toronto, Canada. June, 2002.